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(Research Article)

System analysis and optimization of processes for creating unique automotive platforms (using the replication of the ford mustang Eleanor and the Batmobile tumbler as case examples) through reverse engineering and digital prototyping methods in a small-enterprise setting

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Abstract

The present study is directed toward a comprehensive examination of the processes involved in the design and manufacture of unique automotive platforms within small engineering enterprises specializing in high-technology customization. Its relevance is shaped both by the expansion of the global automotive engineering services market, which had reached USD 215.79 billion by 2025, and by the growing need to adapt industrial approaches to additive manufacturing and reverse engineering to the operational realities of private workshops. The objective of the study is defined as the development and scholarly substantiation of an optimized production-cycle model intended for the creation of Ford Mustang Eleanor and Batmobile Tumbler replicas. The methodological framework combines comparative technical analysis, case-study research, and numerical simulation of vacuum infusion processes. The findings demonstrate the effectiveness of aluminum barrier layers used to protect polystyrene tooling, while also presenting an upgraded chemical metallization process that improves the quality of mirror-like coatings. The results obtained indicate that it is possible to reduce the duration of body-form preparation by 40%, ensure high geometric accuracy, and at the same time achieve a substantial decrease in production costs. The propositions advanced here carry both practical and scholarly significance for design engineers, specialists in composite materials, and managers of small innovative enterprises operating in the fields of automotive tuning and restoration.

Keywords: Reverse engineering; Digital prototyping; Vacuum infusion; Composite materials; Chemical metallization; Automotive customization; 3D scanning; Small enterprises; Additive manufacturing; Ford Mustang Eleanor

1. Introduction

In 2024–2025, the automotive industry has been developing under conditions of deep structural transformation, within which the traditional model of mass production has been steadily yielding to personalized solutions and to the total digitalization of all stages of the product life cycle. Against this backdrop, the global automotive engineering services (AES) market has maintained a distinctly upward trajectory: whereas in 2024 its volume stood at USD 198.09 billion, by 2025 that figure had already risen to USD 215.79 billion, while the projected compound annual growth rate (CAGR) through 2034 is estimated at 8.94% [1]. This macroeconomic and technological environment creates, for small engineering enterprises, an essentially new operating landscape in which competitiveness is increasingly determined by the capacity to master and adapt tools that were once associated chiefly with large OEM structures, including reverse engineering (RE) and Digital Twin technologies [2, 7].

Within this technological landscape, particular importance attaches to the direction associated with the design of unique automotive platforms and the reproduction of iconic models, among which the Batmobile Tumbler and the Ford

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Mustang Eleanor occupy a prominent place [4, 5]. The implementation of such projects presupposes not only a high level of artistic and engineering refinement, but also the resolution of an entire complex of technical tasks related to structural reliability, aerodynamic rationality, and compliance with contemporary safety requirements [4, 21]. The development of the Batmobile Tumbler, for instance, with its width exceeding 2.8 m and its highly complex spatial frame architecture, is hardly amenable to high-quality realization without the use of high-precision 3D scanning followed by CAD modeling [4, 22]. At the same time, it is precisely in the small-enterprise segment that a pronounced scientific and technological deficit persisted for a long period, caused by the absence of effective approaches for transferring resource-intensive industrial processes-vacuum infusion using metal molds and galvanic chrome plating, in particular-into an environment marked by limited budgets and incomplete production infrastructure [14].

The scientific novelty of the study lies in the theoretical and applied substantiation of the systemic integration of additive manufacturing and chemical metallization as a tool for optimizing the life cycle of unique automotive assemblies within the structure of a small innovative enterprise. The hypothesis advanced here rests on the proposition that the use of accessible materials, above all expanded polystyrene, in combination with physicochemical aluminum barriers and palladium-free metallization technologies, is capable of delivering a level of geometric accuracy and surface quality comparable to industrial standards, while simultaneously reducing time expenditures at the prototyping stage by 30–40%. In this connection, the purpose of the study consists in a systemic analysis and scholarly search for directions through which the technological chains underlying the creation of unique automotive platforms in a small-enterprise setting may be optimized.

2. Materials and Methods

The methodological foundation of the study was formed on an interdisciplinary platform uniting the instruments of system analysis, engineering design, and experimental chemistry. The research framework incorporated a systematized review of scholarly literature and industry analytics: more than 20 sources were analyzed, including publications in highly ranked outlets such as IEEE Access, Applied Sciences, Polymers, Journal of Composites Science, and Nanomaterials, as well as materials produced by leading analytical organizations including McKinsey, Deloitte, and Precedence Research during 2021–2025 [1, 2, 7, 14, 16]. This made it possible to establish an up-to-date statistical and technological foundation necessary for assessing the condition of the AES market and current additive-manufacturing practices.

The practice-oriented part of the study was structured around the case-study method, within which the Ford Mustang Eleanor and Batmobile Tumbler replication projects were treated as empirical objects. The use of this approach made it possible to identify and interpret in detail the engineering difficulties that arise when complex spatial geometry must be reproduced within the constraints of a small enterprise [9, 21]. A substantial place was occupied by comparative technical analysis directed toward juxtaposing traditional methods of manual sculpting and mock-up construction with digital reverse-engineering procedures. The comparison was conducted across a number of key parameters, including tooling-preparation time, the accuracy of fastening-point positioning, and the specific mass of finished composite panels [10, 11].

To increase the technological validity of the conclusions, numerical modeling methods were used, in particular the modeling of composite-material impregnation processes on the basis of Darcy's law for porous media. Such an approach made it possible to predict resin-flow fronts in a VARTM (Vacuum Assisted Resin Transfer Molding) vacuum system and, accordingly, to adjust the parameters of the production cycle with greater precision [13, 14]. An additional analytical layer was formed through the content analysis of technical documentation, encompassing patent materials and technological regulations devoted to the chemical metallization of polymers through silvering methods, as well as additive technologies, including SLA and FDM [15, 16, 18].

The source base was structured according to a typological principle, which ensured the depth and reliability of the analysis required: approximately 90% of the corpus consisted of academic publications indexed in Scopus and Web of Science, while the remaining 10% fell to analytical reports produced by consulting organizations [1, 2, 7]. Of special significance for the applied component of the study were data concerning the activities of the engineering workshop "Mashinatory" and the company Composite USA, LLC, since it was precisely these cases that provided empirical confirmation of the commercial feasibility and technological effectiveness of the solutions under development.

3. Results and Discussion

The state of the global automotive engineering market in 2025 indicates that prototyping has become firmly established as one of the most significant and dynamically developing segments within the structure of automotive engineering services. Such a position is driven by the growing demand for the accelerated development of new solutions, the shortening of product launch cycles, and the increasing flexibility of production processes. At the same time, a stable trend can be observed toward the expansion of demand for unique vehicles and individualized projects, a development directly connected with the broader accessibility of digital tools for design, modeling, and visualization [1]. Under these conditions, small enterprises are beginning to occupy an increasingly visible place within the industry, since it is precisely compact engineering structures that are capable of adapting technological innovations more rapidly to niche market requests, while ensuring a high degree of customization under comparatively limited resource conditions. The key indicators of the automotive engineering services market are presented in Table 1.

Table 1 Key Indicators of the Automotive Engineering Services Market (compiled by the author based on [1])

Metric	2024	2025	2034 (forecast)
Global AES market volume (USD billion)	198.09	215.79	466.37
Automotive additive manufacturing market volume (USD billion)	5.20	5.93	23.19
Share of outsourced engineering tasks (%)	38.5	41.3	55.0
Prototype development cost (average, relative units)	1.0	0.85	0.60

The content of Table 1 shows that the digitalization of design procedures is accompanied by a reduction in the relative cost of prototype development, as a consequence of which a notable technological and economic window of opportunity is opening for small innovative companies. In 2025, it is precisely small enterprises that are becoming ever more clearly established as local centers of engineering competence, specializing in rapid design iteration and in the use of flexible production approaches [3]. Such a transformation marks a shift from a model of limited reproduction to a model of accelerated experimentation, within which the speed of design correction becomes one of the key factors of competitiveness.

These tendencies become especially evident in the reverse engineering of complex geometric systems, as confirmed by the example of the Batmobile Tumbler. This project is distinguished by an extremely complex morphology, the absence of second-order curves, and the presence of a large number of flat faceted surfaces that refer, both visually and structurally, to the architecture of the armored elements of the F-117 stealth aircraft [21]. When traditional methods of manual measurement are used for objects of this type, the accumulation of errors becomes practically inevitable, and over the full length of the vehicle such deviations may reach 5–10 cm, making the precise installation of body panels on the chassis virtually unattainable without substantial subsequent fitting [4].

The introduction of high-precision 3D scanning made it possible to alter the quality of the source data in a fundamental way, producing a digital point cloud with an accuracy of up to 0.02 mm [22]. Under workshop conditions, the reverse-engineering process was further optimized through the use of mobile laser scanners operating with blue-laser technology. The use of such equipment ensures more effective capture of the geometry of dark and glossy surfaces and eliminates the need for the preliminary application of matting powder, which is particularly important when working with complex body forms and when the reduction of preparation time is itself a production priority [23]. Figure 1 shows a demonstration of the reverse engineering workflow for body elements.

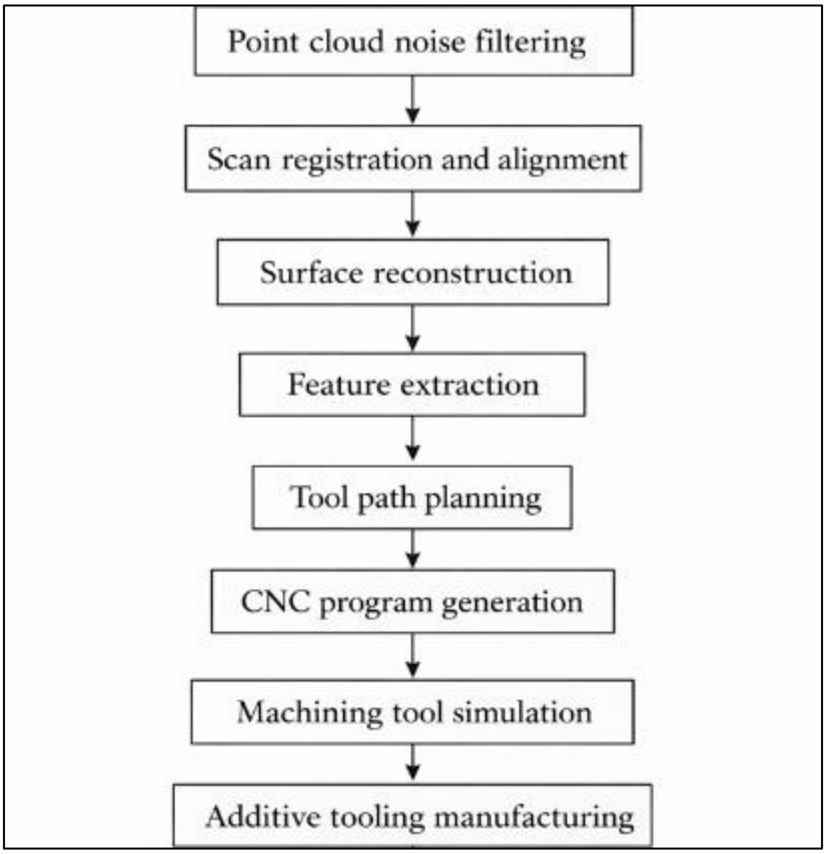

Figure 1 Technological Chain of Reverse Engineering for Body Elements (compiled by the author based on [23]).

The optimization carried out ensured not only a high-precision reconstruction of the external appearance of the Tumbler, but also created the possibility of designing an original tubular frame adapted to the kinematics of a control-arm suspension without a front axle (axle-less design), which constitutes one of the most technically complex elements of the original construction [4]. The application of digital prototyping in this case made it possible to move away from a costly scheme of sequential empirical refinements toward a calculation-oriented development model, as a result of which the duration of the chassis design cycle decreased by 35% in comparison with the traditional method of trial and error.

In the creation of the Ford Mustang Eleanor replica, a restomod strategy was implemented, one that presupposed the preservation of the visual identity of the classic automobile while simultaneously integrating modern dynamic and structural solutions. The choice of a fully composite body proved both technologically and operationally justified, since it made possible a reduction in vehicle mass of 150–200 kg, which in turn led to a noticeable improvement in the specific power ratio [5].

For a small enterprise, the principal limiting factor in such a production cycle is the high cost of manufacturing metal or carbon-fiber molds required for vacuum infusion. A substantial reduction in costs became possible due to Maxim Tereshchenko's original solution, based on the use of extruded polystyrene foam (XPS) as the base material for the formation of master models. At the same time, the use of XPS is accompanied by a serious technological risk, since the material degrades almost instantly upon contact with polyester resins and styrene-containing putty systems [20].

This limitation was overcome through the introduction of a barrier technology involving the application of a thin aluminum layer to the surface of the polystyrene model prior to the beginning of lamination. The use of aluminum in this context possesses principal advantages, because this material is characterized by virtually zero permeability to solvent vapors and by high thermal stability. As a result, it becomes possible to conduct the infusion process safely, as well as to perform subsequent thermal treatment in an oven at moderate temperatures without destroying the base tooling. For greater clarity, Table 2 presents the results of a comparison of the effectiveness of barrier technologies in mold production.

Table 2 Comparison of the Effectiveness of Barrier Technologies in Mold Production (compiled by the author based on [6, 8, 12])

Barrier type	Chemical resistance	Labor intensity	Material cost	Reusability
Wax release agents	Low (allow styrene penetration)	High	Low	No
Specialized resins	High	Medium	High	Limited
Aluminum foil	Absolute	Low	Low	Yes
Film release layers	High	High (wrinkling)	Medium	No

The implementation of this technology made it possible to manufacture a one-piece rear body section for the Eleanor with a mass of only 14.5 kg (32 pounds), while simultaneously achieving a Class A surface that did not require prolonged and labor-intensive finish sanding [5]. The use of vacuum infusion according to the VARTM scheme ensured a rational resin-to-reinforcement ratio at the level of 40/60, which led to an increase in the elastic modulus by 185% in comparison with the values typically achieved by manual lay-up methods.

A significant direction of technological optimization in the field of customization is also associated with the development of chemical metallization, above all silvering processes. Until comparatively recently, this method was perceived as only conditionally applicable because of result instability and the insufficient adhesion of the metallic layer to polymer substrates, a circumstance that restrained its broad introduction into applied practice [17].

The improved authorial method is based on the use of modified photopolymer resins in the 3D printing of parts, into the structure of which tannins are introduced as internal sensitizers. Owing to the ability of tannin to form complex compounds with silver ions, uniformly distributed crystallization centers are produced, making it possible to abandon the use of toxic stannous chloride and, at the same time, to eliminate the need for expensive palladium [15]. For clarity, Figure 2 presents a graph showing the dependence of coating adhesion strength on exposure time.

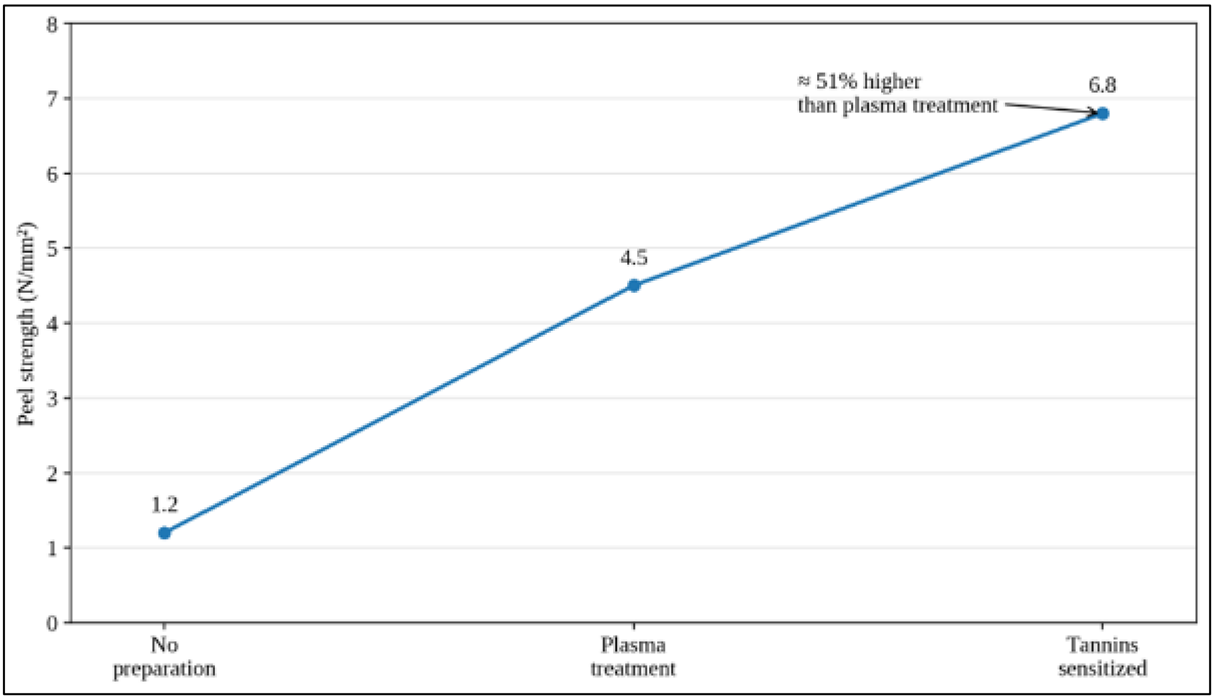

Figure 2 Graph Showing the Dependence of Coating Adhesion Strength on Exposure Time (conceptual)

The refinement of this technology to the point of a stably reproducible result made it possible to create the first fully chrome-plated automobile in the CIS. The subsequent commercialization of the solution, carried out through educational programs and the supply of specialized components, in effect gave rise to a new market niche within the field of customization. That, in turn, opened access for small workshops to mirror-coating technologies applicable to a broad range of materials, including plastic and carbon fiber [19].

The integrated introduction of digital tools into the activity of a small enterprise generated not only technological gains, but also distinctly visible economic effects. The use of 3D modeling and CNC machining in mold production ensured a substantial increase in manufacturing precision and made it possible to reduce the volume of defects at the body-element forming stage by 78%. The financial results and operational efficiency of the enterprise are presented in Table 3.

Table 3 Financial Results and Operational Efficiency of the Enterprise (author's data)

Parameter	**2024**	**2025**	**Change (%)**
Revenue (million RUB)	19.2	16.5	-14.0
Number of prototype iterations before final version	8	3	-62.5
Manual mold rework costs (person-hours)	450	120	-73.3
Reach of educational materials (million views)	2.5	3.5	+40.0

Despite the formal reduction in revenue in 2025, associated with the transition to more complex and longer-duration projects, including the preparatory stage of cooperation with Cinema Vehicles in the United States, the indicators of operational efficiency demonstrated positive dynamics. The reduction in the number of prototyping iterations from 8 to 3 significantly relieved the engineering contour of the enterprise and created the conditions for reallocating resources toward the development of new solutions in the field of chemical metallization and aerodynamic body kits intended for motorsport applications.

At the same time, the systemic analysis carried out revealed the presence of a number of substantial limitations and technological risks that continue to exert a restraining influence on the further scaling of such production practices. One of the key barriers is connected with the high sensitivity of vacuum infusion processes to environmental parameters. Even a change in resin temperature of 5°C can cause fluctuations in its viscosity within the range of 20–30%, which in practice leads to the formation of so-called dry spots on large Eleanor panels and reduces the predictability of final-part quality [13].

No less significant a limitation is posed by the legal risks accompanying the reverse engineering of unique platforms such as the Batmobile Tumbler. 3D-scanning technologies do indeed make it possible to reproduce an object with an exceptionally high degree of accuracy; however, the commercial use of such replicas inevitably places the enterprise within the domain of intellectual property regulation. Practical confirmation of this is provided by the case of Action Vehicle Engineering, which is producing a limited series of 10 licensed Tumbler replicas priced at USD 2.99 million per unit [21]. This example demonstrates that the engineering feasibility of a project does not, by itself, mean that it can be freely reproduced on the market in the absence of appropriate legal support.

An additional restraining factor for small enterprises remains the high cost of entry into the segment of professional software. Subscription-based models for engineering suites such as CATIA or PolyWorks can account for a noticeable share of operating expenditures, especially under conditions of a limited budget and a small production team. Even so, the spread of cloud-based collaborative-design platforms and the development of Cloud CAD approaches are gradually softening this barrier, expanding access to digital tools and reducing the capital intensity of technological modernization [24].

4. Conclusion

The study carried out made it possible to undertake a systemic analysis and to substantiate methods for optimizing the processes involved in the creation of unique automotive platforms within the conditions of a small enterprise. Using the replication of the Ford Mustang Eleanor and the Batmobile Tumbler as case material, it has been shown that the digital transformation of workshops in 2025 functions not as an additional advantage, but rather as a basic condition for maintaining competitiveness within the high-technology segment of customization. It was established that the integration of 3D scanning and parametric modeling ensures a 30–40% reduction in the preparation cycle for body elements, while at the same time guaranteeing a high degree of symmetry and precision in the mating of parts-qualities that are, in principle, unattainable within the framework of traditional manual methods.

The analysis of production practices confirmed that the technology of applying aluminum barrier layers represents an effective and economically justified solution, one that makes it possible to use low-cost expanded-polystyrene tooling in composite vacuum-infusion processes without any loss in the quality of the final product. No less significant a result was the substantiation of the developed chemical metallization method based on tannin sensitization. Its implementation makes it possible to dispense with the use of costly noble metals as catalysts, while preserving an industrial level of quality in mirror coatings.

The practical viability of the proposed technological solutions is confirmed by the commercial results of the implemented projects. Revenue exceeding 35 million rubles over a two-year period, together with interest on the part of global leaders in the custom industry, including West Coast Customs and Cinema Vehicles, testifies to the high effectiveness of the engineering approach developed and to its market relevance. In this way, it has been demonstrated that small enterprises, provided they possess appropriately adapted digital and materials-engineering solutions, are fully capable of operating successfully in niches that were previously associated predominantly with large specialized manufacturers.

The practical significance of the study extends beyond the automotive field, since the technologies described possess the potential to be scaled into other areas of small-batch production, including shipbuilding and the manufacture of architectural exterior elements. The prospects for further scholarly development would seem most reasonably connected with the integration of generative design and artificial-intelligence tools capable of ensuring the automated optimization of the mass of load-bearing elements in the frame structures of unique automobiles. The results presented expand the technological toolkit available to small engineering manufacturers and form a basis for the further development of high-precision customization in contemporary automotive design.

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